PERFORMANCE EVALUATION OF STRUCTURAL LIGHTWEIGHT CONCRETE INCORPORATING ALUMINUM POWDER ANDPUMICE IN FIRE CONDITION

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Abstract

*The basic aim of this research is to study the production and the performance of structural lightweight concrete using pumice stone (PS)as a different replacement of coarse aggregate (25%, 50%, 75% and 100% by volume) and aluminum powder (AP)as an additive by 0.5% of cement weight in the fire condition (with periods up to 2 h, at different temperatures varied of 200-800 °C). The performance was determined by investigating compressive strength, flexural strength, thermogravimetric analysis (*TGA*) and bond strength. As a result, the increase in replacement ratio of PS with afixed content of AP has a positive influence on compressive, flexural strength and bond strength during the exposure to the fire. For examples, the residual bond strength go up in the range 21-53% by increasing PS content from 25% to 100% as a replacement of coarse aggregate by volume. The thermogravimetric analysis curve shows that the early weight loss was at temperatures of 30-120 °C, with arate of weight loss in the range 0.6-1.2%, for all mixtures, while the total weight loss at 800 °C was in the range 14.5-19.6%. Moreover, the compositions of concrete containing PS with AP are the highest resistance to thermal decomposition and the least in weight loss, according to results of TGA.*

Keywords: *structural lightweight concrete, fire, aluminum powder, thermogravimetric analysis, pumice.*

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1. INTRODUCTION

The spread of fires in special buildings and government institutions, Causes huge damages which in turn prompting researchers to work on developing manufactured materials of the buildings to become more fire-resistant. However, the concrete structures need further development to protect the reinforcing steel and keep up concrete strength from the negative effect of fire [1]. It is not easy to protect buildings from fire due to the significant differences in the concrete components [2]. The construction materials technology led to discovering the lightweight concrete where it has many advantages such as sound insulation, low transfer of heat, small structural members, reduction of loads and stresses and low-cost [3,4]. Lightweight concrete (LWC) has good properties of fire resistance, but it needs to increase its compressive strength. There are many ways to get LWC, such as reducing concrete density by creating voids within the cement paste, as well as replacement coarse aggregate by lightweight coarse aggregate [5, 6]. Aluminum powder added to the concrete mix to produce the air voids in the concrete [7]. The pumice fraction used in the mix as a lightweight coarse aggregate, where there is an inverse relationship between pumice volume in concrete and density of concrete [8]. Zardi et al., [9] produced non-structural floating concrete using pumice with different ratios and aluminum powder by ratio 2%, which achieved average compressive strength was 3.15 MPa and average concrete density was 925.49 kg/m^3. Some studies showed similar work [10, 11]. Bingol and Gul[12] discusses impacts of a high temperature of 23-750°C on concrete that containing pumice as replacing coarse aggregate by ratios up to 100%. The results indicated that more significant index on compressive strength, not heating duration, but the increase in temperature. Vilches et al. [13] conduct a pilot investigation about ultra-lightweight concrete after exposure to fire. Hence, in conclusion, the concrete density must reach more than 250 kg/cm3 for achieving a high fire resistance. So far, there is not enough information about structural lightweight concrete which containing pumice stone and aluminum powder together especially after exposure to fire, so was this study.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

Ordinary Portland cement (CEM I 42.5 N) was used and produced according to Egyptian standard specification (ESS 4756-1, 2007) [14]. The chemical composition of materials is shown in Table 1. Silica fume (SF) used as an addition to increase compressive strength and fire resistance. The properties of cement and silica fume are as presented in Table 2. Two types of coarse aggregate used in this work, dolomite and crushed pumice stone (PS) with the maximum size 12 mm. The local natural sand used as fine aggregate. The aggregates properties are as presented in Table 3. Tap water used in mixing with superplasticizer (SP) ADDICRETE BVF tomaintainthe slump of used mixtures within the range (85-95 mm). Aluminum powder (AP) used to lower the weight of concrete and increase the concrete resistance of fire. Table 4 reflects the properties of aluminum powder and superplasticizer.

Table-1: Chemical composition of used powder

Chemical composition (%)	Cement	SF	PS
SiO_2	21.5	95.97	71.23
Al_2O_3	6.2	0.68	13.48
Fe_2O_3	3.1	0.34	1.62
CaO	61.5	0.63	1.83
MgO	2.2	0.05	0.23
K_2O	0.3	0.36	4.89
SO_3	2.6	0.05	0.03
Na_2O	—	0.3	3.6

Table-2: Properties of cement and silica fume

Basic properties		Cement	SF
Specific gravity		3.15	2.15
Fineness (cm2/g)		3555	264498
Setting time (min.)	Initial	139	—
	Final	197	—
Soundness (mm)		1	—
Compressive strength (MPa)	2-days	25.9	—
	28-days	49.3	—

Table-3: Properties of aggregates

Basic properties	Dolomite	Pumice	Sand
Specific gravity (SSD)	2.65	0.96	2.5
Unit weight (kg/m3)	1680	678	1620
Absorption (%)	1.59	37.23	1.87
Fineness modulus	—	—	2.67
Clay and other fine materials (%)	0.17	0.94	1.3

Table-4: Characteristics of Aluminum powder and Superplasticizer

Property	AP	SP
Color	Silver-gray	Brown
Specific gravity (g/cm^3)	2.7	—
Atomic weight	26.98	—
Volumetric mass at 20°C (kg/l)	—	1.16
Shelf life (month)	—	18

2.2 Specimens Production

Many trials were carried out to produce the structural lightweight concrete using aluminum powder and pumice stone together; to get the best mixture that can resist fire. Selected mixtures are used to block heat transferring within the concrete and give the longer age of fire resistance. Pumice is used with different replacement values (0, 25, 50, 75 and 100%) of normal coarse aggregate (dolomite) by volume. Aluminum powderwas used by 0.5% of the cement weight to get suitable voids within concrete where (sand/total aggregate) ratio was 44%. Moreover, cement content was 420 kg/m3, with 12% silica fume, and w/c ratio varied of 0.45 to 0.49. The slump was in range 85-95 mm by using superplasticizer with different ratios of (0.8%-1.8%) of cement content. The mix proportions of concrete mixtures are as shown in Table 5. The specimens were transferred to the curing after casting by 24 h. and the curing in the water tank at temperature 22 °C continued until 28 days.

Table-5: Proportions of concrete mixtures

Mix No	Materials (kg/m^3)							
	Cement	SF	AP	Water	SP	Sand	Dolomite	PS
M1-Control	420	50.4	-	189	7.56	736.43	937.27	-
M2-AP0.5%-PS0%	420	50.4	2.1	193.2	6.72	731.59	931.11	-
M3-AP0%-PS75%	420	50.4	-	205.8	3.36	721.44	229.54	249.47
M4- AP0.5%-PS25%	420	50.4	2.1	189	7.56	735.55	702.11	84.78
M5- AP0.5%-PS50%	420	50.4	2.1	189	7.56	735.55	468.08	169.56
M6- AP0.5%-PS75%	420	50.4	2.1	189	7.56	735.55	234.04	254.34
M7-AP0.5%-PS100%	420	50.4	2.1	189	7.56	735.55	-	339.13

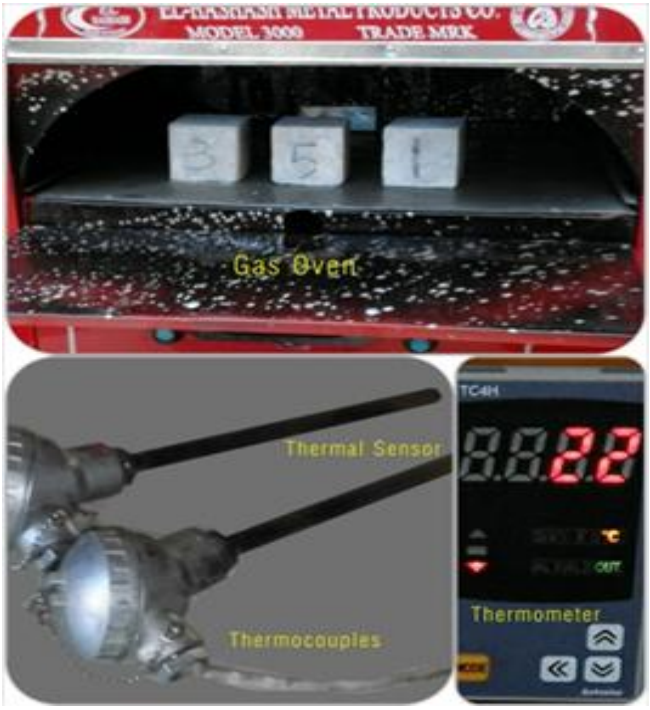
2.3 Fire Procedure and Testing

Concrete samples were exposed to direct fire after one day of finishing curing, i.e., the specimens were left 24 hours to dry in the room temperature before the exposure to the fire, where the samples are directly exposed to fire flame in the gas oven with fire periods 1 h and 2 h, at temperatures 200 °C, 400 °C, 600 °C and 800 °C. The specimens put in the oven for specific periods with measuring fire temperatures constantly during the fire by using thermal sensor (type K) connected with thermocouples (type K) and thermometer (type Autonics TC4H). The measured temperature variations do not exceed ±3 °C in all samples. Fig. 1 shows the gas oven which used in the study. The concrete that exposed to fire is tested after self-cooling of samples even 22 °C in the oven. The compressive strength did according to the ESS No.1658 [15], by cubic samples, size 100 mm. Flexural strength achieved according to the EC of practice issued 2007 [16], by prismatic specimens with the section of 150 x 150 mm and length of 750 mm. The cylindrical specimens of 150 mm diameter and 300 mm height are used for the test of bond strength with steel bar 16 mm that embedded in concrete cylinder center. Eq. (1) represents the bond strength.

$$F_b = P/(\pi \times d \times L) \qquad (1)$$

Where:
F_b = bond strength
P = pull out load
d = bar diameter
L = bar length embedded in the cylindrical sample.

Thermogravimetric analysis (TGA) is carried out on the produced concrete mixtures according to ASTM E1131 [17]to measure the change of specimen weight during exposure to elevated temperatures and finding amount the loss or increase of weight. This test allows the determination of the temperature that makes decomposition of the concrete components. This test was taken about 17 mg from core of the concrete cube (i.e., on depth about 50 mm from surface of cubic) for each mixture as specimen, and the heating was using the thermogravimetric analyzer (Thass-TGA I 1000) in the atmosphere of air with rate 20 °C /min with the range of temperatures from 22.11 °C to 800.02 °C. Furthermore, records the change of sample weight as a function of temperature.



Fig–1: Used gas oven

3. RESULTS AND DISCUSSION

3.1 Unit Weight

Table 6 shows the results of Concrete tests before exposure to fire for 28 days age. The unit weight of concrete specimens was decreased by 12.7%, 18.9%, 27.4% and 33% when the coarse aggregate replaced with pumice stone by ratios of 25%, 50%, 75% and 100% respectively, with using 0.5% aluminum powder in all replacement ratios. The weight loss was 8.6% for the specimen that containing dolomite coarse aggregate and 0.5% AP (M2) compared to the control mix whereas the weight loss was 23.2% for the specimen which containing 75% PS (M3) without AP. The requirements of the unit weight of the structural lightweight concrete are fulfilled according to ASTM C330 [18] by utilizing PS and AP.

Table-6: Results of Concrete tests before fire exposure

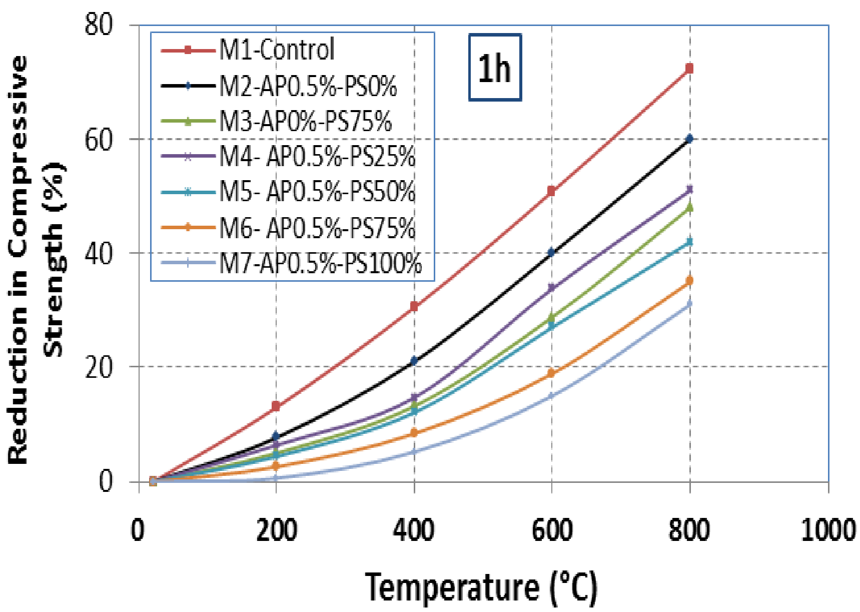
Mix ID	Compressive strength (MPa)	Flexural strength (MPa)	Bond strength (MPa)	Unit weight (Kg/m3)
M1-Control	38.2	6.3	11.1	2341
M2-AP0.5%-PS0%	33.4	5.1	10.2	2139
M3-AP0%-PS75%	19.9	2.4	5.1	1796
M4- AP0.5%-PS25%	31.5	4.4	9.6	2042
M5- AP0.5%-PS50%	27.8	3.7	8.7	1897
M6- AP0.5%-PS75%	23.2	2.9	6.5	1699
M7-AP0.5%-PS100%	16.3	1.7	4.2	1568

3.2 Influence of AP and PS on the Compressive Strength after Fire Exposure

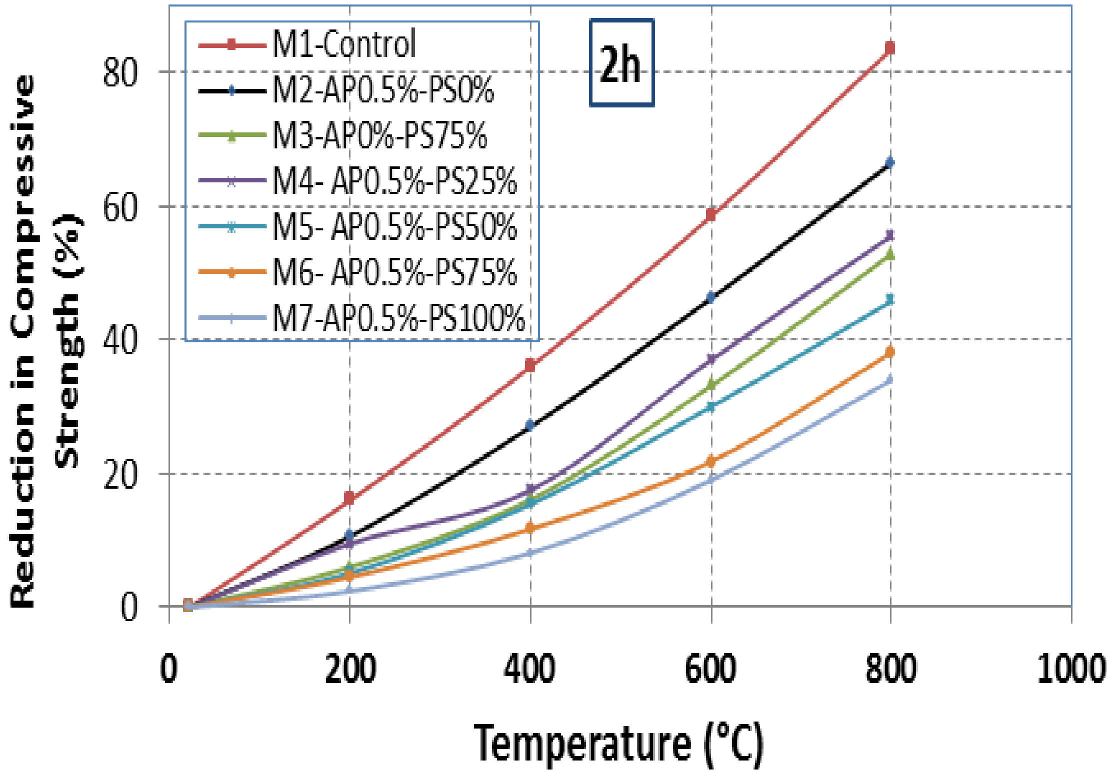
The percentage of loss in compressive strength after fire exposure of the concrete is shown in Figs.2 and 3. The reduction in compressive strength at 800 °C and for a period of 2 h, of the fire was 83.5%, 66.5%, 52.9%, 55.6%, 45.8%, 38.1% and 34%, respectively, for mixtures from M 1 to M 7. Moreover, the rate of loss in compressive strength at same earlier conditions decreased 27.9%, 37.7%, 45.4% and 49.5% by increasing PS content 25%, 50%, 75% and 100% respectively, with a fixed ratio of AP (0.5%) while the rate of loss in strength decreased by 17% and 30.6%, for both M 2 and M 3. Hence, increasing the PS content with AP has a positive effect on the concrete resistance of the fire; this impact attributed to the role that played by them in blocking heat transfer well within the concrete by voids that were formed in the mixture content.

3.3 Influence of Elevated Temperature and Fire Period on Compressive Strength

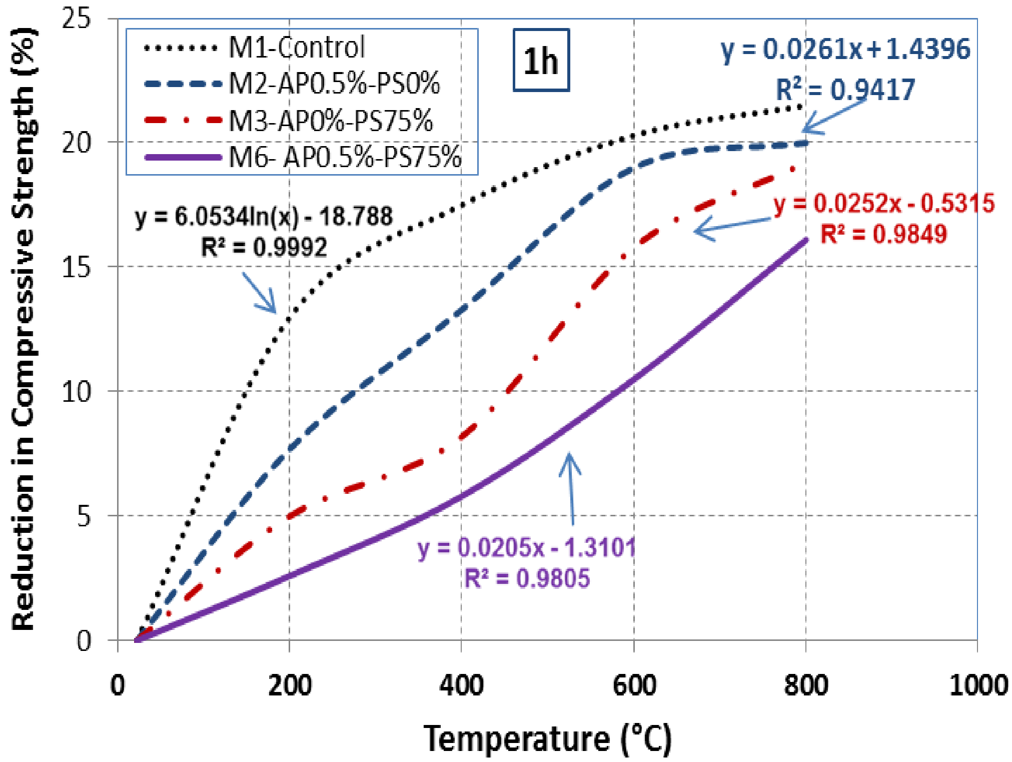
The relation between the loss in compressive strength and the change of temperature at fire periods (1 h and 2 h) is shown in Figs. 4 and 5. Based on results, the compressive strength of M 1, M 2, M 3 and M 6, decreased in the range 13-21.5%, 7.7-20%, 5-19.2% and 2.6-16% respectively, for each 200 °C increase in heat at first hour of the fire. While the reduction in the strength for a period of 2 h, was about 16-25%, 10.6-20.3%, 6-19.8% and 4.5-16.3%, for same mixtures and rate of increase in temperature. Hence, it is clear that higher levels of temperature have the greatest effect in the loss of compressive strength of concrete, then comes the fire period in second place. These results match the results of researchers BingolandGul [12]. As expected, the relationship between compressive strength and temperature is the inverse relationship, where that the reduction in strength is clear when the temperature reaches 200°C. This reduction due to partial loss of hydration results and these chemical changes of the internal structure of concrete leads to micro-cracks on concrete surfaces as shown in Fig. 6.



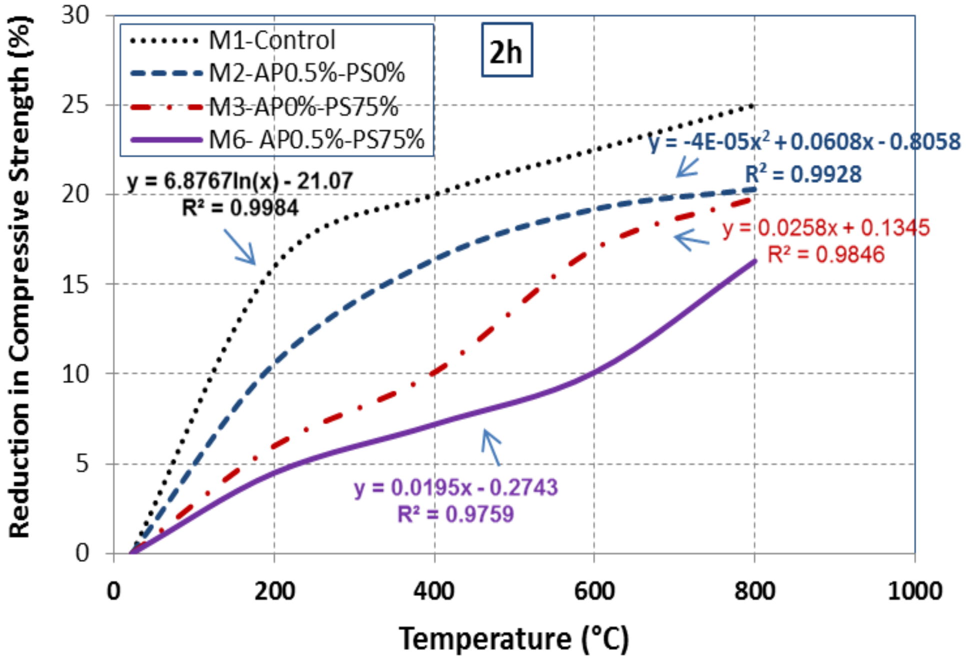
Fig–2: Percentage loss in compressive strength after exposure to1 h of fire



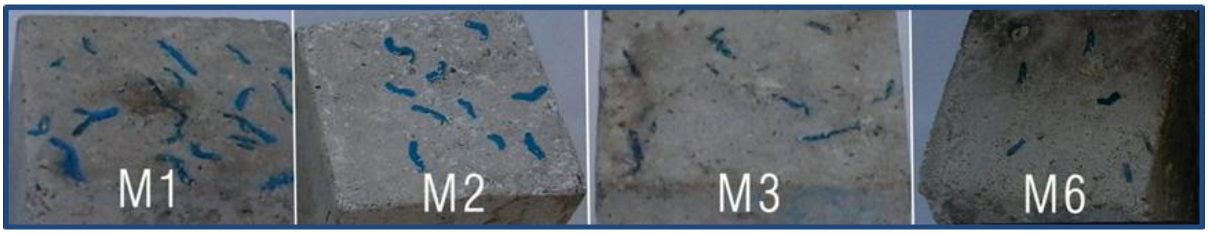
Fig–3: Percentage loss in compressive strength after exposureto 2 h of fire



Fig–4: Compressive strength loss- temperature change curve at 1 h of fireexposure



Fig–5: Compressive strength loss- temperature change curve at 2 h of fireexposure



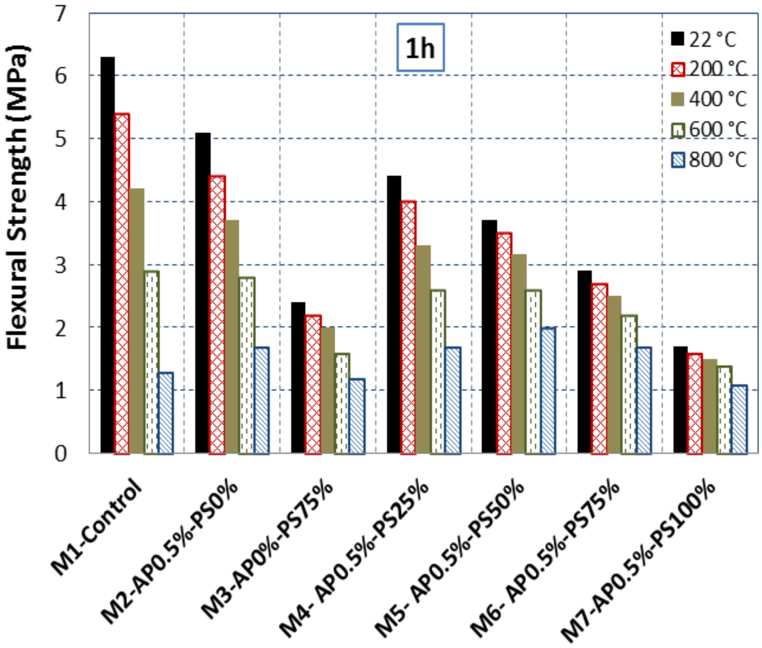
Fig–6: Surfaces texture of test specimens after fire exposure at800 °C

3.4 Influence of AP and PS on Flexural Strength after Fire Exposure

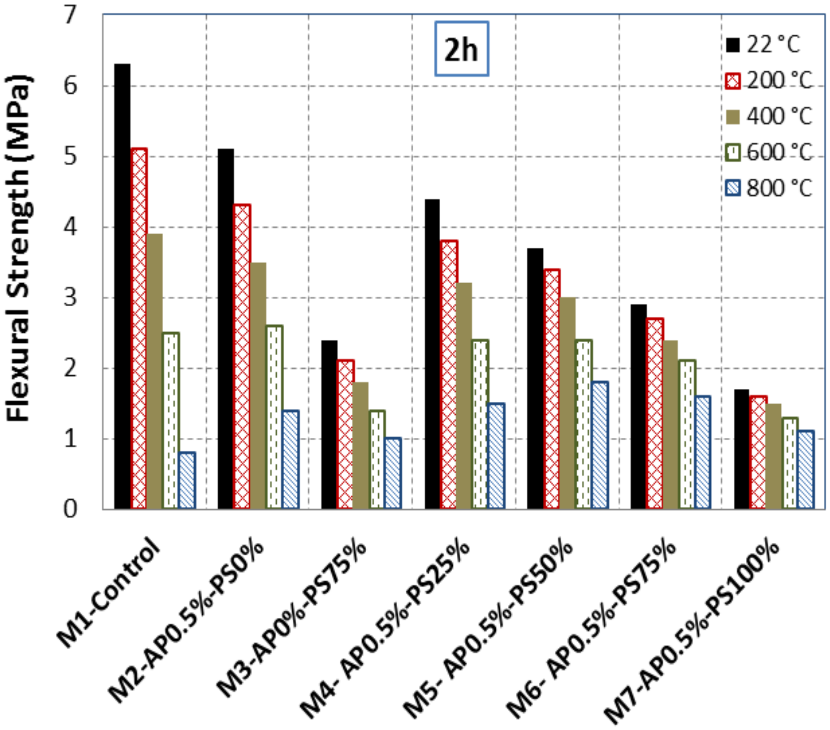
The flexural strength values after (1 h and 2 h) of the fire are shown in Figs.7 and 8 which show the impact of temperature and fire period on flexural strength. Generally, flexural strength decreased by increasing exposure duration to fire and temperature. Figs. 9 and 10show percentage of loss in flexural strength after fire exposure. The reduction in flexural strength at 800 °C and for a period of 2 h, of the fire was about 86%, 72%, 58%, 65%, 49%, 42% and 35% respectively, for mixtures from M 1 to M 7.Furthermore, the rate of loss in flexural strength at the same earlier temperature and fire duration decreased about 21%, 37%, 44% and 51% by increasing PS content 25%, 50%, 75% and 100% respectively, with a fixed ratio of AP. While the rate of loss in strength decreased 14% and 28%, for both M 2 and M 3. Also, the negative effect of the fire on the strength was in all concrete mixes, but the specimen containing PS with AP has the higher residual flexural strength then comes concrete made of PS without AP and finally comes concrete that containing AP without PS. This positive effect of concrete made of PS with AP because the specimen is more porous because of using AP as well as PS that used as lightweight coarse aggregate, so obstruction of heat transmission becomes greater**.**

3.5 Influence of Temperature Level and Fire Period on Flexural Strength

The relation between the loss in flexural strength and change of temperature at fire periods (1 h and 2 h) is shown in Figs. 11 and 12.Generally, increasing temperature affects the flexural strength negatively that clearly shown in all mixes, where that the flexural strength of M 1, M 2, M 3 and M 6, decreased in the range 14-25%, 12-20%, 6-18 and 4-16% respectively, for each 200 °C, go up in heat in first hour of the fire, while the reduction in the strength for a duration of 2 h, was in the range 18-26%, 14-23%, 9-19 and 5-17%, for same mixtures and the rate of increase in temperature. Hence, the rate of reduction in the strength was increased by increasing temperature; it was found that the higher loss of the strength in the range 600-800 °C also, there is the slight decrease in the strength with the change of fire duration from 1 h to 2 h. It is clear that the relationship is reversed between the flexural strength and increase of temperatures for all mixes, but there is a difference in the rate of reduction; where that the specimen containing PS with AP was the lower in the loss of strength.



Fig–7: Flexural Strength of concrete after exposure to 1 h of fire



Fig–8: Flexural Strength of concrete after exposure to 2h of fire

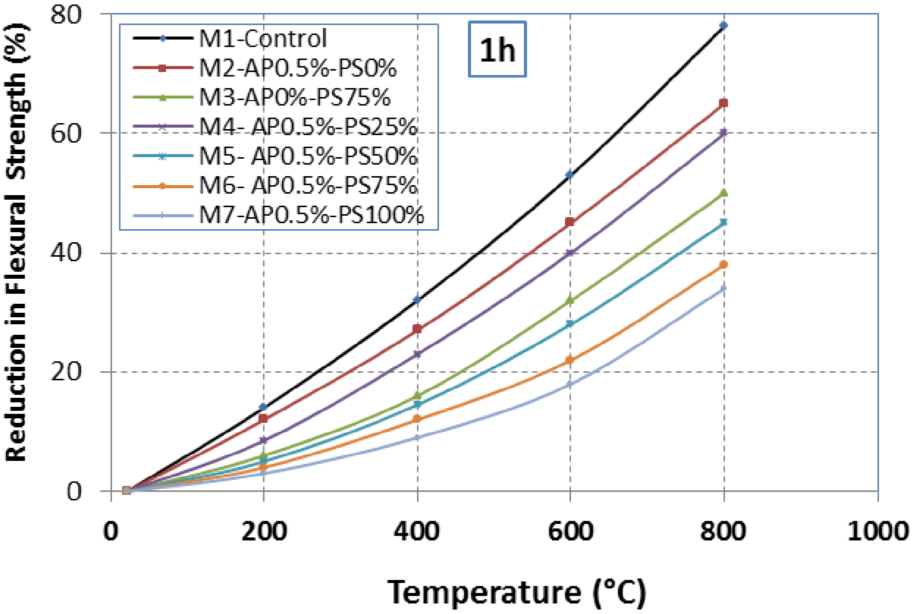
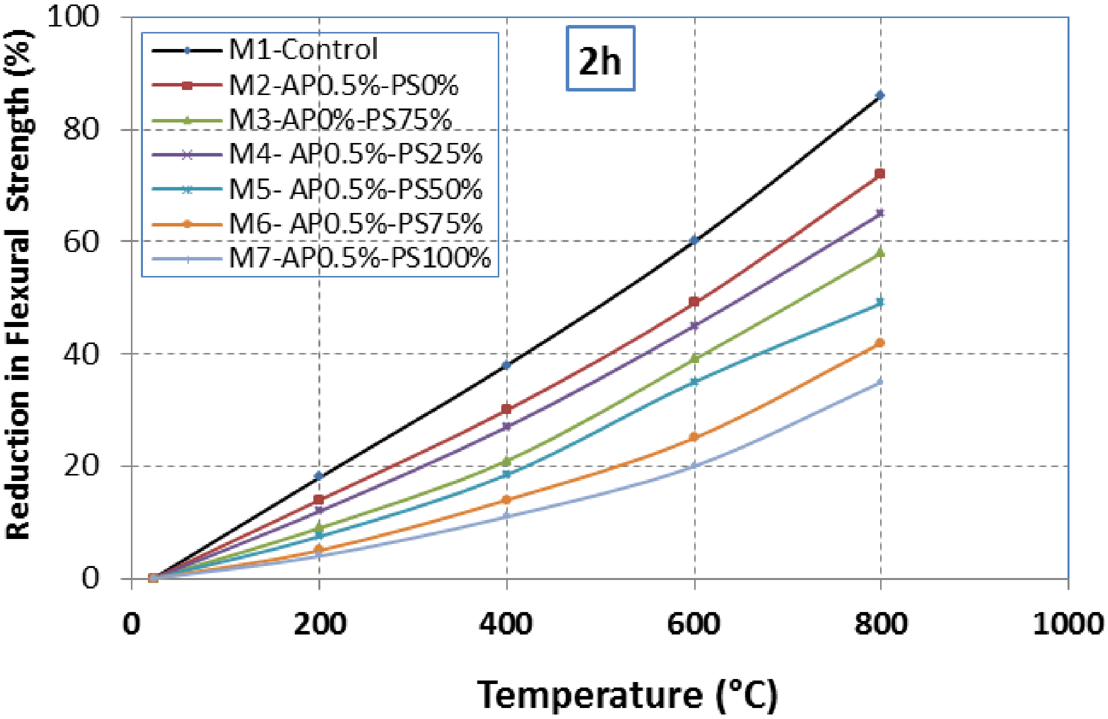
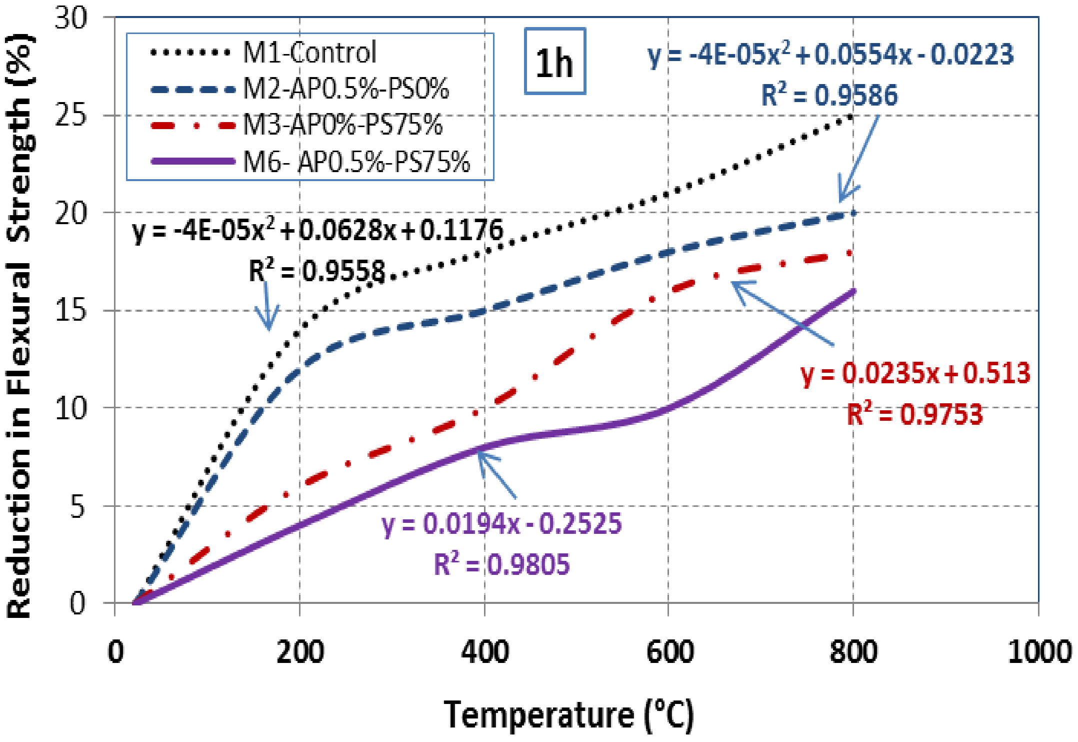


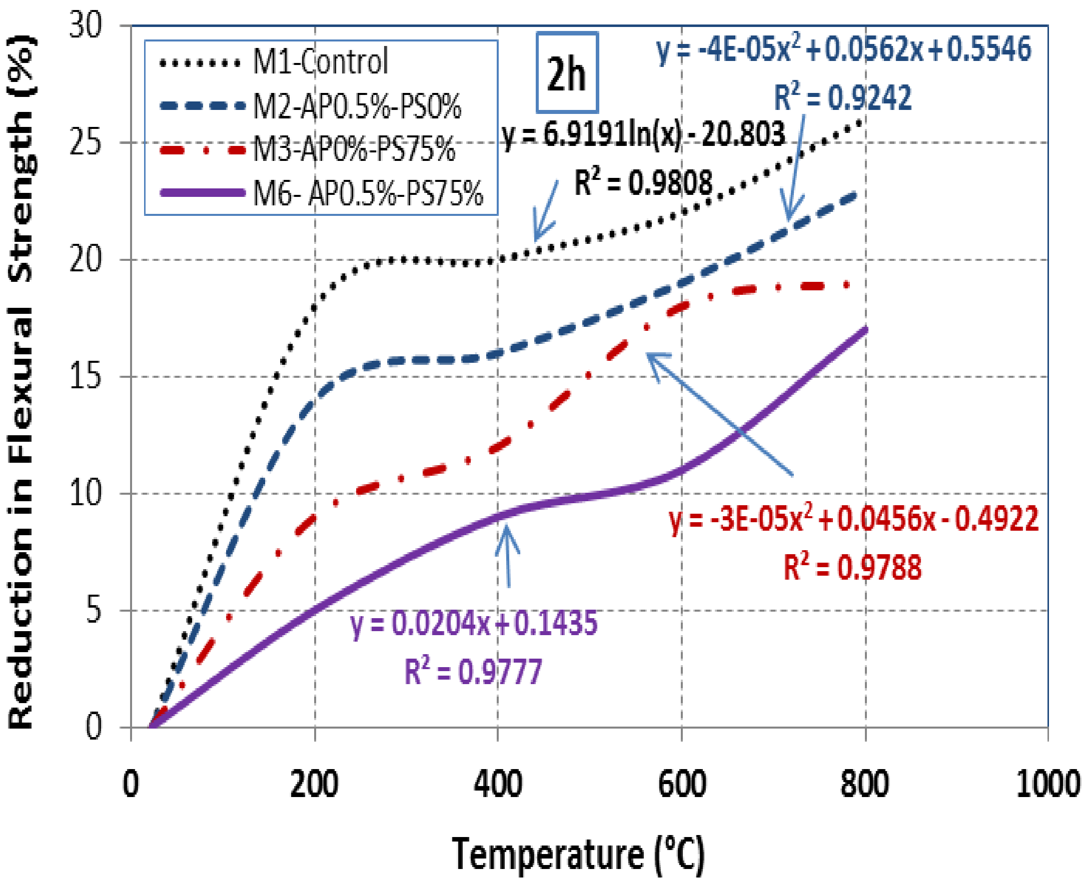
Fig – 9: Percentage of loss in flexural strength after exposure to 1 h of fire



Fig–10: Percentage of loss in flexural strength after exposure to 2 h of fire



Fig–11: Flexural strength loss- temperature change curve at 1 hof fireexposure



Fig–12: Flexural strength loss- temperature change curve at 1 h and 2 h of fireexposure

3.6 Influence of AP andPS on the Bond Strength after Fire Exposure

The pull-out test was done specimens after exposure to fire with different levels of temperature and fire periods (1 h and 2 h). The results were shown in Figs. 13 and 14. In general, the bond strength decreased by increasing fire period in all concrete mixes, whereas the bond strength at 800 °C and for a period of 2 h, of fire was 0.3, 1.2, 1.4, 2, 3, 2.7 and 2.2 MPa, respectively, for mixtures from M 1 to M 7 whereas the strength at same earlier temperature and for duration of 1 h of fire was in range 0.9 and 2.7 MPafor mixtures from M 1 to M 7. The percentage of loss in bond strength after the fire exposure of concrete is shown in Figs. 15 and 16.The rate of reduction in bond strength was not found constant. The loss in bond strength at 800 °C for a period of 2 h, of the fire, was about 97%, 87.4%, 71%, 79%, 65%, 57.1% and 46.9% respectively, for mixtures from M 1 to M 7. Moreover, the rate of loss in bond strength at same earlier temperature and fire duration decreased by about 18%, 32%, 39.9% and 50.1 % by increasing PS content by 25%, 50%, 75% and 100% respectively, with a fixed ratio of AP (0.5%) while the rate of loss in the bond strength decreased by about 9.6% and 26%, for both M2 and M3. The increase in PS content with AP has a positive influence on bond strength during exposure to fire until 800 °C and for a period of 2 h.

3.7 Influence of Elevated Temperature and Fire Period on Bond Strength

The relation between the loss in bond strength and change of temperature at fire periods (1 h and 2 h) is shown in Figs. 17 and 18. Generally, the loss rate of the bond strength of all mixtures rises with increasing the temperature, while the bond strength of M 1, M 2, M 3 and M 6 decreased in the range 18-27%, 16-25%, 11-21.3 and 8-17.1% respectively, for each 200 °C, goes up in heat in the first hour of the fire. Moreover, the reduction in the strength for a period of 2 h was in the range of (20-29%, 17-27.4%, 12.4-22.6 and 9-18.1%) for the same mixtures and rate of increase in temperature. It was found that the rate of loss in the bond has not changed significantly with the change of fire duration, but there is an influential change in the rate of the bond loss with increasing levels of temperature. Thus, the relation is reverse between the reduction in bond strength and the increase of temperature for all mixes, while there is a difference in the rate of reduction for each mix.

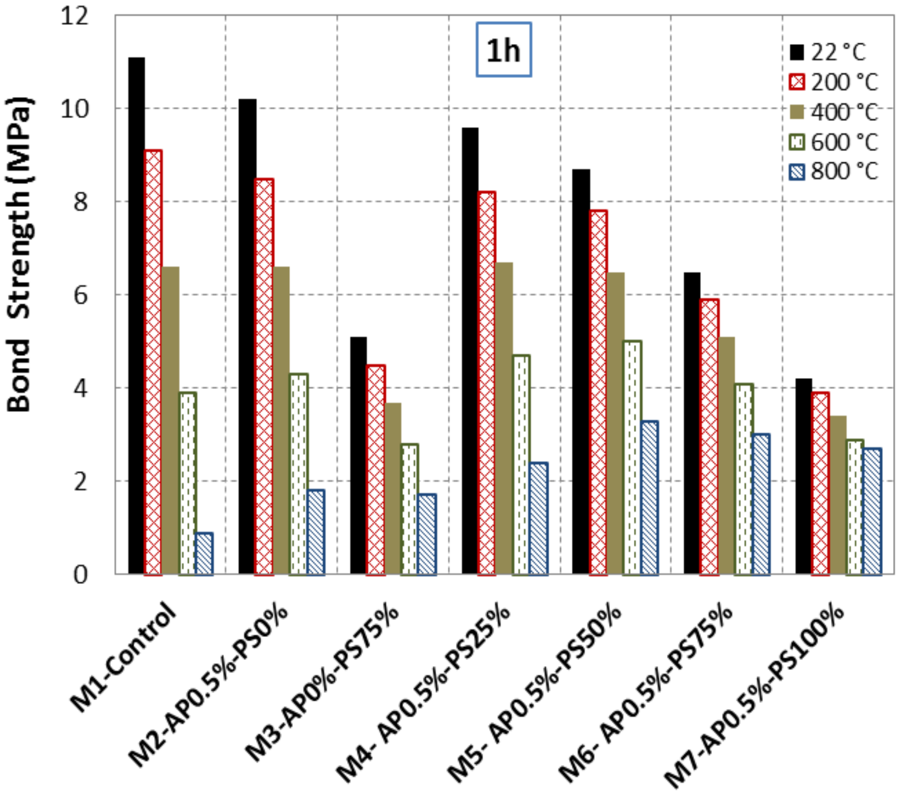
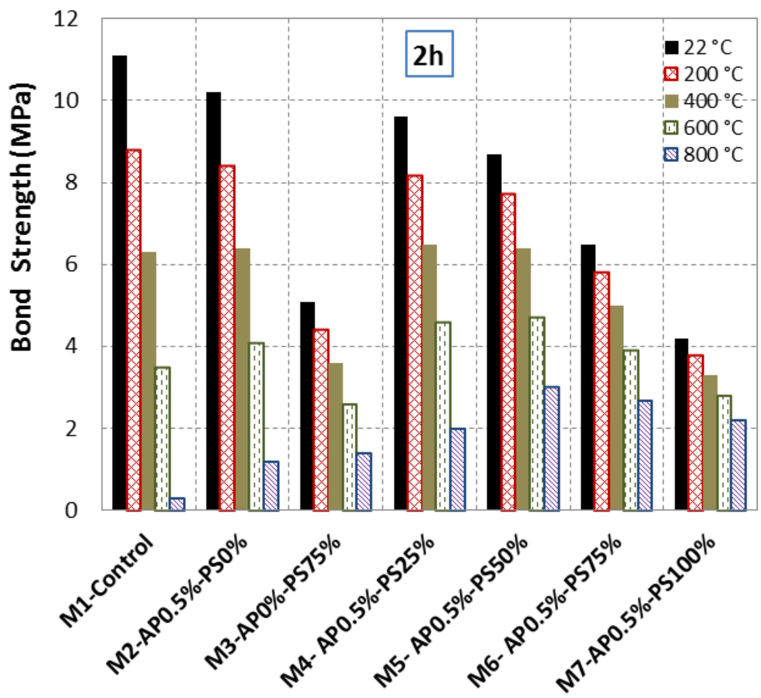
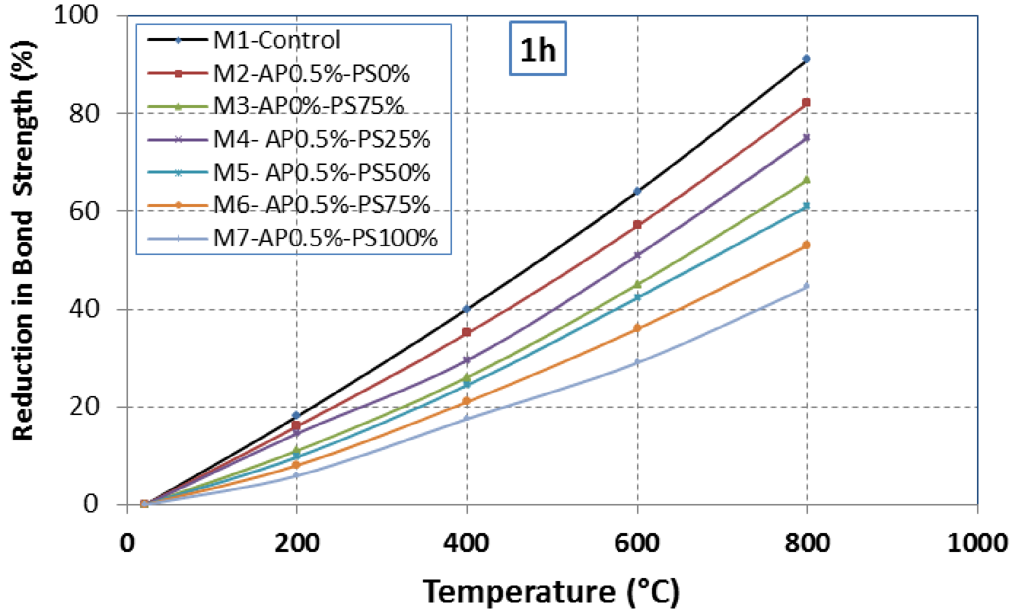


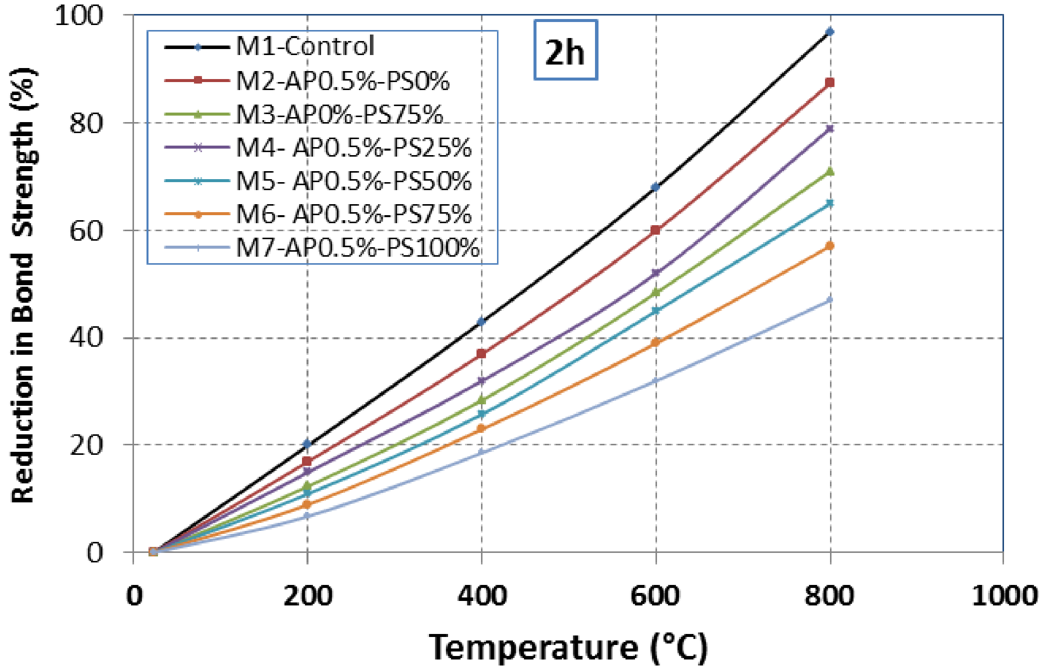
Fig –13: Bond Strength of concrete after exposure to 1 h of fire



Fig–14: Bond Strength of concrete after exposure to 2 h of fire



Fig–15: Percentage of loss in bond strength after exposure to1 h of fire



Fig–16: Percentage of loss in bond strength after exposureto 2 h of fire

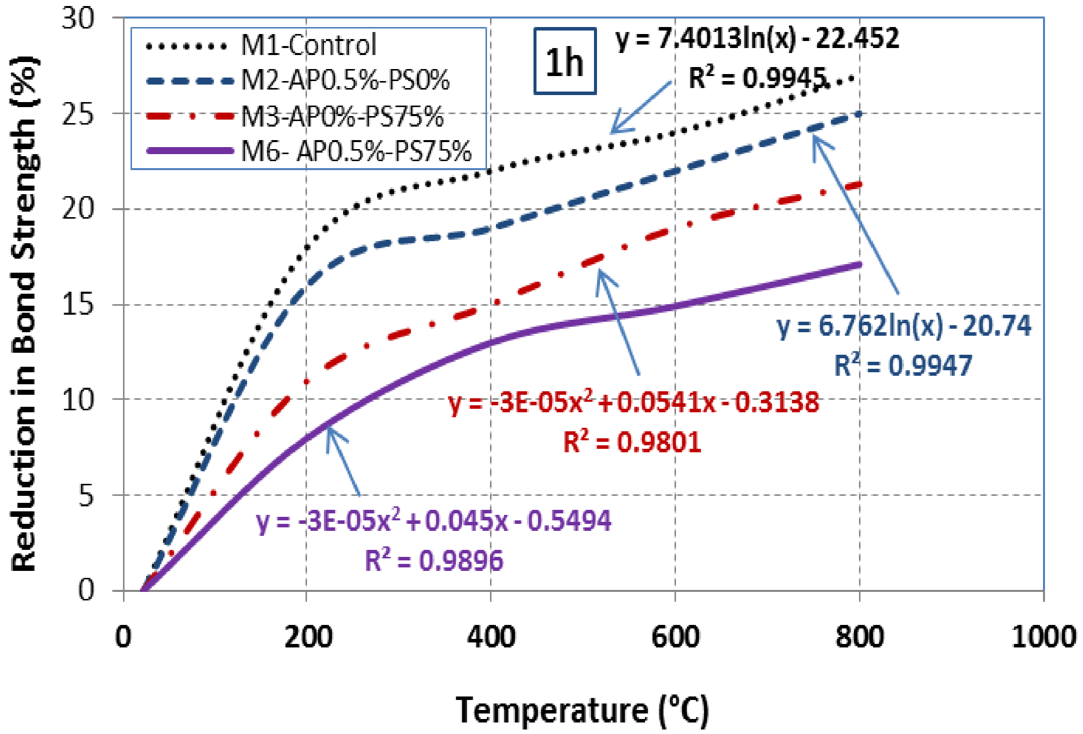


Fig-17: Bond strength loss- temperature change curve at 1 h of fire

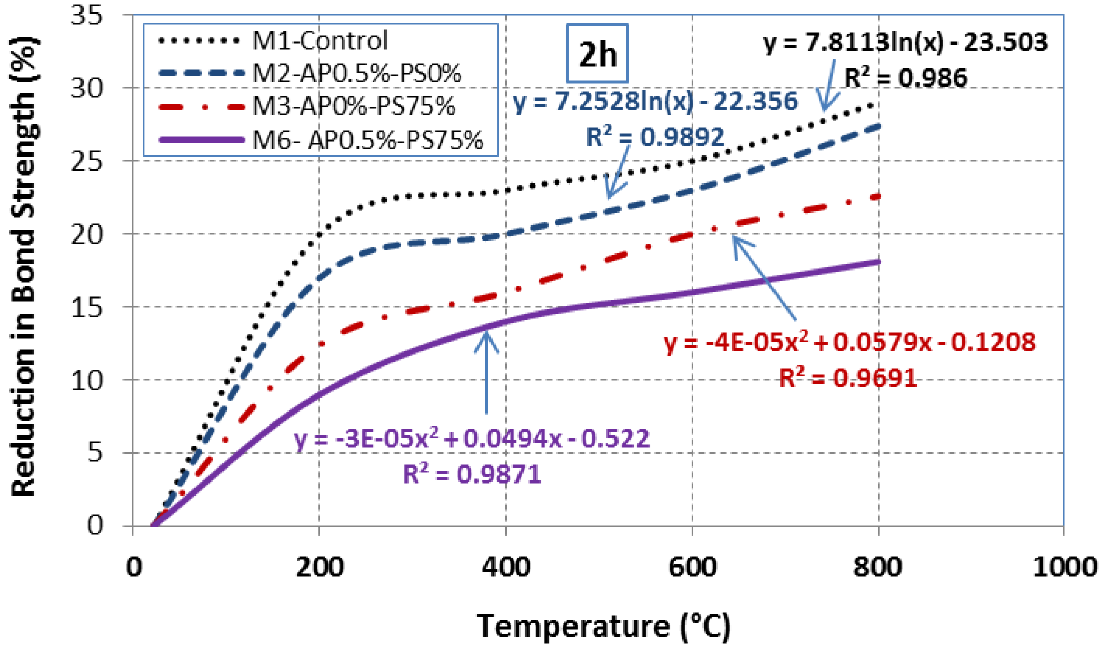


Fig-18: Bond strength loss- temperature change curve at 2 h of fire

3.8 Influence of Thermogravimetric Analysis on Concrete Containing AP and PS

The resulting curve from thermogravimetric analysis (TGA) is shown in Fig. 19. The TGA curve shows that the early weight loss was at the temperatures in the range 30-120 °C, with the rate of weight loss in all mixtures was in the range 0.6-1.2%, at temperature 120 °C. The early loss is due to evaporation of free water inside concrete and partial dehydration of the Components of hydration during heating. Moreover, at temperatures from 120 to 460 °C, the reduction in weight has increased in all mixes by varied of 7.4-11.2%, at temperature 460 °C. The increase in weight loss is attributed to disintegration of calcium hydroxide from $Ca(OH)_2$ (s) to CaO (s) + H_2O (g), also the dehydration of ettringite and C-S-H gel and calcium aluminates hydrate. Thus, the temperatures when became in the range 460-800 °C, the rate of weight loss increased by about 7.1-8.4%, by increasing temperatures by 340 °C, whereas the total weight loss at 800 °C was in the range 14.5-19.6%. The total loss increased as a result of the decarbonisation of CaCO3 in the hydrated compound, where calcium carbonate transformed from $CaCO_3$ (s) to CaO (s) + CO2 (g). Furthermore, it is clear that the compositions of concrete containing PS with AP are the highest resistant to thermal decomposition and the least in weight loss.

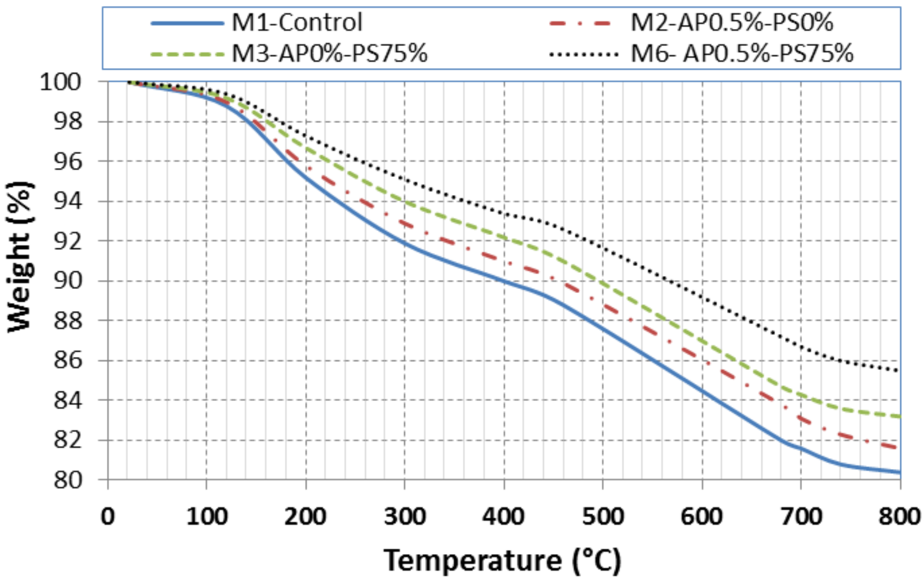


Fig-19: Thermogravimetric analysis

4. CONCLUSION

In this research, the performance of structural lightweight concrete in the fire studied after its production using aluminum powder with pumice and comparing its performance with two types of concrete, and the conclusions were as follows:

1 The results refer to the possibility of production of structural lightweight concrete with high resistance to fire by utilizing pumice stone by a ratio of 75%as replacement of coarse aggregate with 0.5% aluminum powder as an additive of cement content.

2 The concrete containing pumice stone with aluminum powder which exposed to fire achieves the highest compressive strength, flexural and bond compared to concrete containing AP only or PS only.

3 The increase in pumice stone content with the fixed ratio of the aluminum powder(0.5%) has a positive influence on compressive, flexural and bond strength during exposure to fire until 800 °Cand for a period of 2 h.

4 The rate bond strength loss has not changed significantly with the change of fire duration, but there is an influential change in the rate of the bond loss with increasing temperatures.

5 The Thermogravimetric analysis (TGA) shows that the early weight loss was at temperatures of 30-120 °C with the rate of weight loss in all mixtures in the range 0.6-1.2% while total weight loss at 800 °C was in the range 14.5-19.6%. Furthermore, the compositions of concrete containing pumice stone with aluminum powder are the highest resistant to thermal decomposition and the least in weight loss.

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